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GAMMA HEATING MEASUREMENTS IN A MIXED RADIATION FIELD*

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ABSTRACT

Gamma heating measurements have been made in a low-Z assembly irradiated with 14-MeV neutrons and (n,n') gammas produced by a Texas Nuclear Model 9400 neutron generator. The assembly is composed of 144 magnesium sleeves (5cm x 5cm x 60cm x 2 mm thick) filled with graphite to simulate a fusion blanket test module. Heating measurements were made in the mid-line of the assembly using a proportional counter operating in the Continuously-varied Bias-voltage Acquisition (CBA) mode. The neutron induced atomic recoil signal was rejected by observing the signal rise-time differences inherent to radiations of different LET. The experiment was modelled using the one-dimensional radiation transport code ANISN/PC. The operating limits of this technique were identified by comparing measurements made at different positions in the assembly and then comparing these measurements to the calculated flux.

I. INTRODUCTION

The measurement of heating in fusion blanket test assemblies can provide valuable engineering data for the design of potential fusion blankets. In the present generation of test assemblies, the energy deposition is insufficient for a direct measurement of the heating. The total heating in these blanket assemblies has two components: (1) heating resulting from neutron interactions with the blanket materials, and (2) gamma ray interactions with the blanket materials. An estimate of the total heating in a given assembly can be made if a measurement of either component of the total heating is applied to a radiation transport calculation that models that assembly.

A method to measure the gamma energy deposition in a broad energy mixed gamma and neutron environment with a proportional counter was developed at Argonne (ANL).^{1,2}

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A cubic irradiation pile formed of 144 (5cm x 5cm x 60cm x 2mm thick) magnesium sleeves filled with rectangular graphite pieces was assembled to provide low-Z scattering, in an attempt to simulate the radiation scattering in a fusion test blanket. A Texas Nuclear Model 9400 neutron generator is used to provide a radiation environment similar to that of DT fusion. A schematic of the irradiation pile and the neutron generator is presented in Fig. 1.

Initially the neutron spectrum at both the front and back of this assembly was measured along the mid-line with a liquid scintillator. The results from a series of heating measurements made with a proportional counter along the mid-line of the assembly are presented in this article. The one-dimensional transport code ANISN/PC was used to calculate the expected neutron and gamma spectrum in the mid-line of the assembly. The ANISN results and the neutron spectrum measurements provide the basis for analysis of the gamma heating measurements.

II. THEORY

Dosimetry techniques (TLDs, calorimetry, liquid scintillators, and proportional counters) all have some difficulty treating the combined neutron and gamma response that constitutes total heating.¹ All dosimeters interact with the radiation field present in a given measurement. Unfortunately the signal they generate is not a simple function of the deposited energy. That is, a given detector may be more sensitive to either the gamma component or the neutron component, or vice versa. Thus it is possible to design a detector such that the response to one component of the radiation field is maximized, and the signal due to the other is rejected. Some dosimeters (TLDs, calorimeters) report only accumulated effects. Since such devices are not able to differentiate between gamma and neutron heating, they are not directly applicable to the type of measurement considered here.

G.

50 cm

144 5cm x 5cm x 60cm x 2mm Mg sleeves filled with rectangular graphite pieces

Note: drawing not to scale

Figure 1. Schematic of the irradiation assembly.

Both liquid scintillators and gas filled proportional counters can differentiate between the responses due to different radiations. Liquid scintillators are poor dosimeters, as their signal output is a rather complicated function of event energy and the event type.³ The last choice, the proportional counter, can in principle be made to report energy deposition in its confines with a rather simple response. This is possible through careful choice of the fill pressure, a proportional counter can be made to conform to the small cavity limit of cavity ionization theory (Bragg-Gray conditions).^{2,4,5} Furthermore, by selecting a gas mixture that approximates the effective atomic number (Z) of the counter's walls, the charged-particle response in the gas (hence reported signal) is made equivalent to the charged-particle response in the counter's walls.⁶

In conducting a measurement over a broad energy range the bias voltage applied to the proportional counter should be adjusted so that the gas-amplification of the counter provides sufficient boost for weak signals, yet avoids the Geiger-Mueller region. In practice this is achieved by utilizing the continuously-varied bias-voltage acquisition (CBA) mode.^{1,2} The CBA is a software driven data acquisition routine that sweeps a counter between predetermined minimum and maximum

bias-voltage values corresponding to the minimum and maximum allowable gas-amplification settings. The magnitude of the signal and the rate of the signal rise-time with respect to the magnitude are recorded.

The gamma and neutron induced signals are separated by data analysis software. Signal separation is possible because the differential spatial energy-loss of different charged-particles depend on the kinetic energy, the charge and the mass of each charged-particle. This can be seen from the Bethe-Bloch equation for differential spatial energy loss:⁷

$$\left\langle \frac{de}{dx} \right\rangle = - \frac{4\pi N_a z^2 \bar{Z} e^4 \rho}{(m_e c^2) A \beta^2} \left[\ln \frac{2(m_e c^2) \beta^2 \gamma^2}{I} - \beta^2 \right]$$

where

z = atomic number of projectile,
 $\bar{Z}$ = atomic number of target,
 A = gram atomic weight,
 ρ = density of target,
 βc = velocity of the particle.

The equation states that for particles of different masses and the same initial kinetic energy, the energy loss per unit path length for the more massive particle is greater than that of the other. That is the more massive

particle loses its energy in a shorter distance. The differential spatial energy-loss is directly related to the rate and duration of the signal rise-time. A positively charged neutron induced atomic recoil atom losing energy in a proportional counter will generate a cloud of secondary electrons as it loses its energy. This secondary electron cloud and its electron avalanche then migrates along field lines to the anode of the counter. The reported signal is just the induced voltage on the anode arising from the secondary electrons as they impact the anode. The rate of the rise time will depend directly on the number of electrons created at the point of interaction: hence it is dependent upon the energy-loss per unit path length. So that the greater the energy loss, the greater the rise time rate. That is, the neutron-induced energetic charge particles generate signals with fast rise-time rates in proportional counters such that the rise-time rate for a neutron induced signal is greater than the rise-time rate of a gamma induced signal. The duration of the signal is dependent upon the dispersion of the electron avalanche across field lines; the larger the initial electron cloud, the larger the duration. In the software routine all the signals are sorted by energy (magnitude of the signal pulse). At each energy the distribution of signal rise-time rates for that energy is examined, and the larger rate events are removed from further processing. The remaining signals are the sum of the gamma induced events and those neutron induced events of very low energies.

III. RESULTS

The experiment consist of irradiating a cubic assembly formed of 144 (5cm x 5cm x 60 cm x 2mm thick) magnesium sleeves filled with rectangular graphite pieces with the output of a Texas Nuclear Model 9400 neutron generator placed 50cm from the front face of the assembly. A schematic representation of the experiment is presented in Fig. 1. Heating measurements are made with the proportional counter placed in the mid-line positions labelled by reference number in Fig. 1.

At the beginning of the experiment the neutron spectra at the front and rear of this assembly were measured by a liquid scintillation detector, these spectra appear as Fig. 2a, and Fig. 2b. In Fig. 2a, the neutron spectrum has a sharp peak at 13 MeV with a small ripple at 2 MeV and some events at energies in between. The peak at 13 MeV is from neutrons produced in the D-T fusion reaction after scattering with the Al and Fe in the target assembly of the neutron generator and 50cm of air. The ripple at 2 MeV is the result of inelastic scattering and some D-D fusion from deuterium adsorbed onto the target. The other signals are the scattered

component of the 14 MeV neutrons. At the back of the assembly (Fig. 2b), the neutron spectrum is that of neutrons thermalized by scattering.

Fig. 2a. The measured neutron spectrum at the front of the assembly.

Fig. 2b. The measured neutron spectrum at the back of the assembly.

Portions of the measured heating data are presented in Figs. 3a through 3d. These graphs represent the rise-time rate distributions for 25 keV events at the four mid-line positions. The neutron induced recoils represented by the fast rise-time rate events decline noticeably as the counter is positioned further away from the source. The gamma-induced electrons represented by the slower rise-time rate events decline correspondingly.

Calculations of the neutron and gamma spectra in the assembly were made with the code ANISN/PC. In these calculations, the assembly is treated as an infinite slab of

Fig. 3a. The rise-time rate distribution at 25 keV for position P1.

Fig. 3b. The rise-time rate distribution at 25 keV for position P2.

Fig. 3c. The rise-time rate distribution at 25 keV for position P3.

Fig. 3d. The rise-time rate distribution at 25 keV for position P4.

Fig. 4a. The calculated neutron spectrum at the front of the assembly.

Fig. 4b. The calculated neutron spectrum at the back of the assembly.

homogeneous graphite and magnesium, irradiated by a 14.8 MeV neutron source at the left boundary. The calculated neutron spectrum at front of the assembly is presented in Fig. 4a. The calculated neutron spectrum at the back of the assembly is presented in Fig. 4b. Comparing Figs. 4a and 4b to Figs. 2a and 2b, good agreement is observed between the calculated and measured neutron distributions.

The bulk of the gamma radiation field is produced by inelastic scatter of neutrons off of the target housing assembly. Some contribution is derived from absorption reactions that occur in the D-T generator's target housing assembly. The more significant of these reactions at 14MeV are:

1. $^{27}\text{Al} (n, \text{non}) ^{28}\text{Al}$ at $\sigma = 0.9\text{b}$ ($E_\gamma = 1.78$ MeV) $t_{1/2} = 2.25\text{m}$
2. $^{27}\text{Al} (n, \alpha) ^{24}\text{Na}$ at $\sigma = 120\text{mb}$ ($E_\gamma = 2.75, 1.37$ MeV) $t_{1/2} = 15\text{h}$
3. $^{27}\text{Al} (n, \alpha) ^{24}\text{Na}$ at $\sigma = 120\text{mb}$ ($E_\gamma = .47$ MeV) $t_{1/2} = 20\text{ms}$ (metastable state)
4. $^{54}\text{Fe} (n, 2n) ^{53}\text{Fe}$ at $\sigma = 50\text{mb}$ ($E_\gamma = 1.3, 1.0, .7, .3$ MeV) $t_{1/2} = 2.5\text{s}/8.5\text{m}$

In steady state operation, one would expect distinct peaks of the gamma distribution to appear at 1.78 MeV, and 0.47 MeV. In order to keep the modelling simple, an initial energy of 2 MeV was assigned the incident radiation in the gamma slowing down problem. While this does not reflect accurately the physical situation, the general shape and magnitude of the gamma propagation distribution is calculated. Figs. 5a and 5b represent the gamma energy distribution at position 1 and position 4 in the assembly. These calculations provide a quantitative feel for the gamma propagation in the assembly.

Fig. 5a. The calculated gamma spectrum at position P1.

Fig. 5b. The calculated gamma spectrum at position P4.

In this experiment the data are sorted by the magnitude of the recorded signal. The magnitude of a given pulse is directly related to its kinetic energy. The energy response of the counter was determined by injecting tritium into the counter and associating the channel into which the last datum falls with the maximum beta energy.²

The data are organized into a distribution of the number of events vs. event energy. The gamma heating is then give by the following formula:

$$\text{heating} = \sum_{i=1}^m \frac{E(i) \times N(i)}{CD \cdot t}$$

In this formula;

$E(i)$ is the energy of the i^{th} channel,

$N(i)$ is the number of events in the i^{th} channel,

t is the collection time,

CD is the mass of the counter fill gas.

Determination of the heating is a straight forward exercise once data collection and signal separation are performed. The following table gives the measured heating values at the four positions.

Table 1.
Measured Gamma Heating Values
for the four positions

Position	t(sec)	CD (g)	Heating (w/g)
P1	7103	0.00915	1.35E-10:7%
P2	7287	0.00915	8.23E-11:7%
P3	5677	0.00915	6.75E-11:12%
P4	7496	0.00915	3.15E-11:10%

IV. DISCUSSION

The calculated neutron spectra provides qualitative agreement with the measured neutron spectra. The 14.8 MeV neutron population falls off in the calculation as a function of distance in the assembly, and the observed rise-time rate distributions (Figs. 3a through 3d) show a similar decrease in the number of fast rise-time rate events. From the data it is seen that the present method for signal separation is limited by the amount of high energy neutrons present at the point of the measurement. At high neutron energies, the recoil population is also of high energy and the signal separation technique works well. However, at low neutron energies the energetic recoil population decreases, and the signal separation technique based on the rise-time rate differences fails. This result could be predicted from the Bethe-Bloch equation for charged-particle energy loss. According to the Bethe-Bloch equation a massive particle of low initial energy may lose energy at the same rate per unit path length as a less massive particle of higher energy. The implications of this breakdown are: (1) The present technique for gamma heating is excellent for a mixed gamma and fast neutron environment. (2) In a mixed gamma and low energy neutron environment, the technique tends to over-report the gamma heating since the detector still responds to the gamma-rays in the same manner but also counts the signals generated by the low energy neutrons (which are no longer distinguishable from the signals generated by energetic gammas).

V. SUMMARY/FUTURE DIRECTIONS

The ability to measure gamma heating in a mixed gamma and fast neutron environment with cylindrical proportional counters is demonstrated. The physical limitations of using a proportional counter as a dosimeter in a mixed gamma and neutron field were explored. The relationship between energy

deposition in the proportional counter's fill gas and the energy deposition in the counter's walls remains to be determined. Calculations of the gamma spectra in the fill gas and in the wall material will be made with ANISN/PC. These spectra can be combined with the mass stopping powers of the appropriate materials to provide a calculational estimate of the gamma heating.

The CBA acquisition technique was found to perform up to initial expectations. Its utility as a detector driver and data acquisition system bear further exploration. The CBA can be used to perform spectra and energy deposition measurements for a variety of voltage driven detectors.

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